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Method of Maintaining the Required Values of Surface Roughness and Prediction of Technological Conditions for Cold Sheet Rolling

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The paper is based on results obtained from topography of surfaces of sheets rolled from deep-drawing steel of the type KOHAL grade 697, non-alloy low-carbon structural steel EN 10263-2:2004 and aluminium. The presented results document correctness of the assumption that the rolling force F_{roll} increases with the increasing reduction Δh and the quality of the rolled surface is improved at the simultaneous increasing of strength of rolled sheets and the decreasing of size of structural grains. The experiment was performed on the two-high rolling stand DUO 210 SVa, which enables only non-continuous technology in contrast to the rolling mill with continuous reduction on one sheet in several degrees on rolling trains, in consequence of which the obtained height parameters of the section are in close correlation with the predicted dependence. Contribution of the work consists in the creation of a mathematical model (algorithm) for predicting technological parameters of the two-high rolling stand DUO 210 SVa at change of the absolute reduction Δh, for example for a deep-drawing steel of the type KOHAL grade 697 and non-alloy low-carbon structural steel PN EN 10263-2:2004 and aluminium, and also in the development of a method of calculation applicable to any material being rolled in general, because the authors have found that various materials can be differentiated by a derived analytical criterion I_{KP}. This criterion is a function of ratio between the modulus of elasticity of reference material and that of actually rolled material. The reference material is here deep-drawing steel of the type KOHAL grade 697. Verification was carried out by measuring changes of final surface roughness profile and final strength of rolled sheets of the stated materials in relation to reductions and those were compared with theoretically predicted values. It is possible to identify and predict on the basis of this algorithm an instant state of surface topography in respect to variable technological conditions. On this basis it is then possible to calculate and plot individual main technological parameters.

Keywords: Surface topography, rolled sheet quality, cold longitudinal rolling, absolute reduction, rolling force.

1. INTRODUCTION

THERE are several tendencies in the global development of flat steel rolling that are characteristic of the late 20th and early 21st centuries: increased quality requirements imposed on cold-rolled sheets, increased demand for ultra-thin cold-rolled sheets (structural grades with thickness of 0.3 mm and less), and desire to decrease energy consumption at all stages of production of cold-rolled sheet. These tendencies have stimulated the development of various methods for cold-rolling process modelling because recognized mathematical models used in steel mill control systems did not permit calculation of rational and cost-effective technological modes [1].

Maintaining the high quality of material requires good knowledge of relation between the instant state of quality of the rolled material and technological parameters for possible increase of output [2].

Development of science and technology and application of new knowledge into practice increases the importance of the issue of surface quality of components. This largely affects both their service life and reliability, and mainly accuracy of operation, noisiness, resistance to corrosion, and wear and fatigue strength depend on it. Control of surface quality is nowadays a very important part of preparation of surfaces for all types of technologies used for their creation [3].

The basis for surface evaluation is formed by the measured parameters, which, however, provide generally only a partial view of some properties of the surface. It turns out that mainly the practical usability of the existing and required parameters for evaluation of the functional properties of surfaces should be given more attention. This would contribute not only to more qualified understanding of the relationship between the surface and its function in a broader context, but it would also confirm the importance of evaluation of surface topography [4].

2. FACTORS INFLUENCING QUALITY OF THE ROLLED SHEETS

Final quality of the rolled product created by cold longitudinal rolling depends on numerous factors, participating in the forming process [5]. The objective is to determine the final quality of surface, which is a function of geometric characteristics and input factor of the used technology. Evaluation of quality of created surfaces can be assessed on the basis of micro-geometric characteristics [6], [7]. Fig.1. presents a basic overview of input factors of rolling process in relation to the rolled product output parameters. The parameters, which have the most influence on the surface roughness profile at cold rolling and on which this work concentrates, are marked with red dashed line.

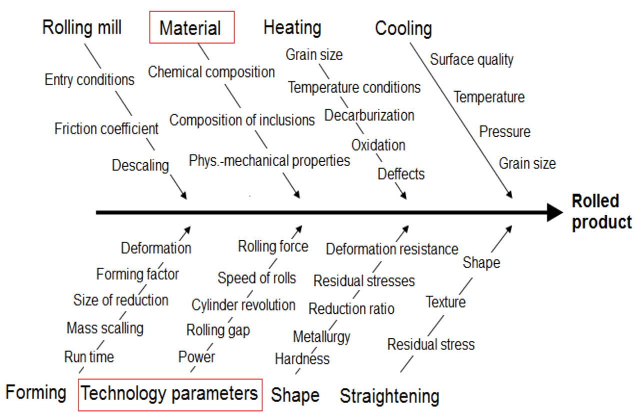

Fig.1. Ishikawa's diagram of rolling system [5].

During any change of some of the main technological parameters (Table 1.) the rolled material adapts and changes its original structural-deformation properties [8].

Table 1. Parameters of experimental rolling stand DUO 210 SVa.

Parameter	Dimensions
Distance between stands	380 mm
Diameter of working rolls	210 mm
Maximal rolling force	350 kN
Rolling speed	0.5 – 1.2 $m{\cdot}s^{-1}$
Sheet width	0.4 – 100 mm
Maximal reduction	10 mm
Rolling gap	20 mm
Electric drive output	34 kW
Electric drive voltage	380 V

Fig.2. Two-high rolling stand DUO 210 SVa.

Such changes of technological parameters occur when it is necessary to increase the output. If the influence of an increase of the rolling speed, rolling pressure or material reduction is not sufficiently respected, the structural-deformation state of material at the output can be affected [9]. It is possible to prevent, even at high requirements to quantitative parameters of production, possible negative impacts on quality of the final product by ensuring the continuous control of material and surface quality during the rolling process in real time, but also by the use of the verified theoretical prediction at design of technology [8]. It must be noted that the data presented in Table 1. are experimental parameters of the two-high rolling stand DUO 210 SVa (Fig.2.).

Two-high rolling stand is the basic structural type, which is nowadays used less frequently. Its advantages are good reduction capacity, straightening effect and realisation of special surface finish of strips (polishing, matt finishing and draining of strip surfaces).

3. SUBJECT & METHODS

To carry out our experiment, i.e. to investigate the influence of technological parameters on surface topography, we chose etched sheets made of deep-drawing steel of the type KOHAL grade 697 and aluminium with dimensions 150 x 31 x 2.52 mm. The sheets were rolled by plastic deformation (Fig.3.) on the laboratory two-high rolling stand DUO 210 SVa. The sheets marked as 1C, 2C, 3C, 4C, 5C were rolled on the two-high rolling stand DUO 210 SVa at the Technical University in Košice 2-7 times at the rotational speed of the rolls of $v_{roll} = 0.7\ m{\cdot}s^{-1}$ (Table 2.). Thickness of sheets was measured by micro-metre with accuracy of measurement of ± 0.01 mm [10].

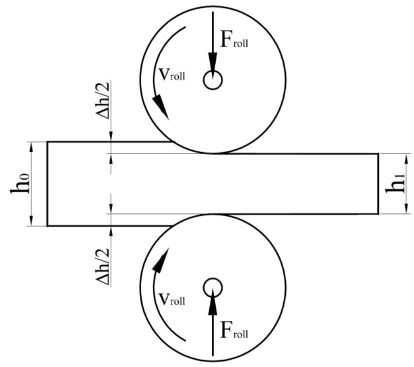

Fig.3. Principle of deformation at longitudinal rolling.

The higher reduction Δh was required, the higher was the number of passes of the sheet through the rolling stand. The original sample marked as 0C did not pass through the rolling stand for reason of mutual comparison of the samples.

Table 2. Technological parameters of created samples.

Sample	Δh[mm]	Picture
0C	-	
1C	0.38	
2C	0.96	
3C	1.27	
4C	1.56	
5C	1.73	

4. Measurement of rolling force

Rolling force on the two-high rolling stand DUO 210 SVa was measured at rolling of deep-drawing steel by metallic strain gauges (Fig.4.), which were at rolling of sheets fixed to this stand [5].

Fig.4. Detail of placement of strain gauges in the rolling stand [6].

The rolling force was measured at the rolling speed of 0.7 m·s^{-1} (Fig.5.) for all sheets made of deep-drawing steel, which are marked as 1C-5C, and it varied from 67.9 kN to 145.1 kN [5].

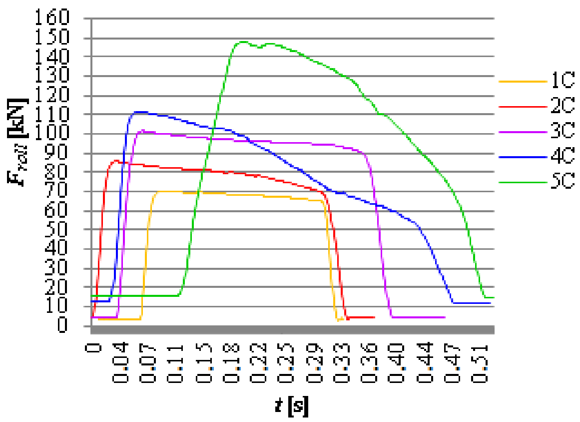

Fig.5. Graphical presentation of evolution of rolling force in time at the rolling speed of 0.7 m·s^{-1} [6].

The higher the required reduction, the higher the rolling force and also the smoother the surface of the rolled product, as it is shown graphically in Fig.6. [5]. This relation is valid for all experimental sheets, with the exception of the sheet made of the deep-drawing steel 2C. For rolling of this sheet higher rolling force was required than for the sheet 3C.

5. Measurement of surface topography

Measurement and evaluation of surface topography represents an independent part of metrology. Special methodologies and measurement devices enable obtaining of the data that are necessary for characterisation of quality of the controlled surface [4]. The height parameters defined in the axis Z are determined by heights of peaks and valleys or by their combinations [4]. The height parameters on the cold rolled sheets made of deep-drawing steel were the height parameters of surface topography measured by roughness meter SurfTest SJ401 and by optical profile-meter MicroProf FRT [4]. The measured surface was always 1.6 x 1.6 mm (Fig.6.). It was established from the findings obtained at measurement that topography of the rolled sheet was influenced at plastic deformation by geometry of working rolls of the rolling stand (namely by the deformation zone). The geometry of the zone of deformation is determined by the area of contact between the metal and the rolls (Fig.7.).

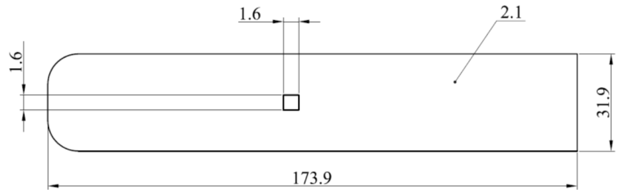

Fig.6. Diagram of the sample 1C with reduction of 0.38 mm with marked measured area of 1.6 x 1.6 mm.

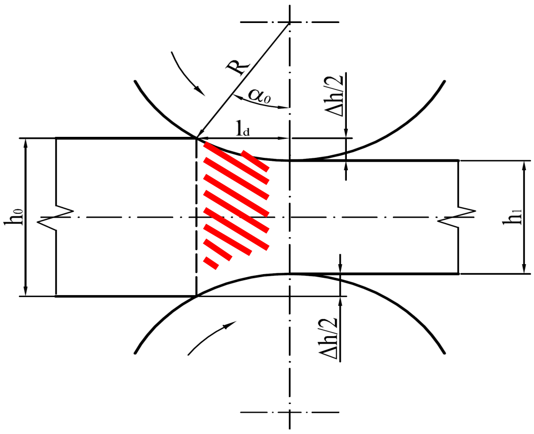

Fig.7. Deformation zone at longitudinal rolling.

6. Prediction of technological parameters

The basic objective is to achieve better material properties in comparison with conventional rolling (strength, toughness, plasticity, etc.), hence the necessary knowledge of individual parameters that influence the rolling [11], [12], [13].

The satisfactory technological parameters of the two-high rolling stand DUO 210 SVa (satisfactory rolling force F_{roll} [N], satisfactory mean arithmetic deviation Ra [μm], length of the deformation zone l_d [mm] and others) were determined for rolled sheets made of deep-drawing steel (Table 3.) at the rolling speed v_{roll} = 42 m·min^{-1} by regression equations.

Table 3. presents numerically regression equations from graphical representation of dependence of absolute reduction of the rolled sheet from deep-drawing steel and aluminium on technological parameters of the two-high rolling stand DUO 210 SVa. Determination coefficients (reliability values), which enabled comparison of true values of technological parameters of the two-high rolling stand DUO 210 SVa and their estimates, were used for

verification of reliability of these explicit functions. Values of determination coefficients for the dependence Δh on technological parameters varied between 0.80 and 1.00.

On the basis of these findings we created an algorithm for the Matlab program for mathematical modelling of the above relations.

The equations in Table 3. were modified for use of the algorithm also for other materials by relation of the material plasticity constants K_P (1)

$$K_P = \frac{10^{12}}{E^2} \quad . \tag{1}$$

Modulus of elasticity in tension E was chosen as a comparative parameter. In this case it was Young's modulus of elasticity of deep-drawing steel of the type KOHAL (E_{PK}=186 700 MPa) and aluminium (E_{PAl} = 70 000 MPa). The constant according to the equation (1) for the deep-drawing steel of the brand KOHAL is K_{PK} = 28.69, and for the aluminium it is K_{PAl} = 204.08. It was established that it was possible to use the index proportion

$$I_{Kp} = \sqrt{\frac{K_{PK}}{K_{PAl}}} \tag{2}$$

implemented into regression relations to reduction, for good differentiation of individual materials in the course of rolling. The constant for the deep-drawing steel of type KOHAL is K_{PK} = 28.69 and is taken as reference parameter in the following calculations.

Mathematical model for prediction of technological parameters of the two-high rolling stand DUO 210 SVa at the change of the absolute reduction Δh is based on these regression equations both for the deep-drawing steel of the brand KOHAL grade 697 and for aluminium (Fig.8.), as well as, generally, for any rolled material. For clarity, only these two materials are given in the graph. The reason is a great difference in input mechanical parameters, and thus, also more marked difference in theoretically predicted values. Curves for non-alloy low-carbon structural steel PN EN 10263-2:2004 would be, in the graph concerned, analogically localized between these boundary materials. Respectively in consideration of its parameters E_{PN}=125580 MPa and K_{PN} = 63.41019.

Legend and comments concerning the results in Fig. 8: Q_{frollK} - satisfactory forming factor for KOHAL [-], n_{rollK} - satisfactory number of revolutions for KOHAL [s^{-1}], n_{rollA} - satisfactory number of revolutions for aluminium [s^{-1}], v_{rollK} - satisfactory rolling speed v_{roll} for KOHAL [m·s^{-1}], F_{rollK} - satisfactory rolling force F_{roll} for KOHAL [N], σ_{sK} - satisfactory surface tension σ_s for KOHAL [N·m^{-1}], σ_{sA} - satisfactory surface tension σ_s for aluminium [N·m^{-1}], F_{rollA} - satisfactory rolling force F_{roll} for aluminium [N], v_{rollA} - satisfactory rolling speed v_{roll} for aluminium [m·s^{-1}], Q_{frollA} - satisfactory forming factor for aluminium [-], Ra_A - satisfactory mean arithmetic deviation Ra for aluminium [µm], Ra_K - satisfactory mean arithmetic deviation Ra for KOHAL [µm].

Table 3. Determination of satisfactory technological parameters of the rolling stand DUO 210 SVa at rolling of other materials.

Satisfactory technological parameter	**Linear regression (explicit function)**
satisfactory rolling speed v_{roll} [m·s^{-1}]	$v_{roll} = -109.56 \cdot \Delta h \cdot I_{Kp} + 167.65$
satisfactory rolling force F_{roll} [kN]	$F_{roll} = 50.77 \cdot \Delta h \cdot I_{Kp} + 40.73$
satisfactory number of revolutions n_{roll} [s^{-1}]	$n_{roll} = -166.07 \cdot \Delta h \cdot I_{Kp} + 254.12$
satisfactory mean arithmetic deviation Ra [µm]	$Ra = -0.21 \cdot \Delta h \cdot I_{Kp} + 0.85$
satisfactory forming factor Q_{Froll} [-]	$Q_{Froll} = 3.99 \cdot \Delta h \cdot I_{Kp} + 1.13$
satisfactory length of zonal deformation l_d [mm]	$l_d = 5.28 \cdot \Delta h \cdot I_{Kp} + 4.59$
satisfactory average height of the rolled sheet h_s [mm]	$h_s = -0.50 \cdot \Delta h \cdot I_{Kp} + 2.52$
satisfactory horizontal projection of the contact surface of the rolled product on the working part of the roll S_h [mm^2]	$S_h = 191.87 \cdot \Delta h \cdot I_{Kp} + 127.47$
satisfactory surface tension σ_s [N·m^{-1}]	$\sigma_s = 4.67 \cdot 10^{-5} + 354.27 \cdot \Delta h \cdot I_{Kp}$

Designation of the curves of the functions is analogous to designation of equations for their calculation according to Table 3. The prediction model shows here the significant difference in behaviour of the main functions in the process of material rolling - in this case relatively rigid deep-drawing steel of type KOHAL and relatively soft aluminium. Then the technologist can easily determine calculated values of the required technological parameter for the selected reduction Δh from the diagram and select the final quality of surface roughness profile Ra (or also for required material hardening by rolling, i.e. increase of strength Rm). The optimal technological parameters of the rolling process for any material can be read from the graph (vertical lines) for the desired surface modifications Ra and the appropriate reduction of the thickness Δh. According to the prediction graph, constraints in limit values of the size of reductions Δh_{lim} for any material can also be specified. The limit size of reduction Δh_{lim} is clearly defined by a value on the axis for Δh, where the rolling speed v_{roll} converges to zero.

Specifically, for KOHAL Δh_{limK} is of 1.6 mm and for aluminium Δh_{limA} it is of 3.8 mm. Other factors defining the size limit of reduction Δh_{lim} are technical parameters of the rolling stand DUO 210 SVa. These are maximal technical values of the rolling speed, rolling force and maximal reduction ($v_{rollmax}$ = 72 m·min^{-1}, $F_{rollmax}$ = 350 kN, Δh_{max} = 10 mm), as shown in Table 1. A set of interest functions and materials may be, according to the above mentioned scheme, interactively extended as required by the technologist using the application MATLAB.

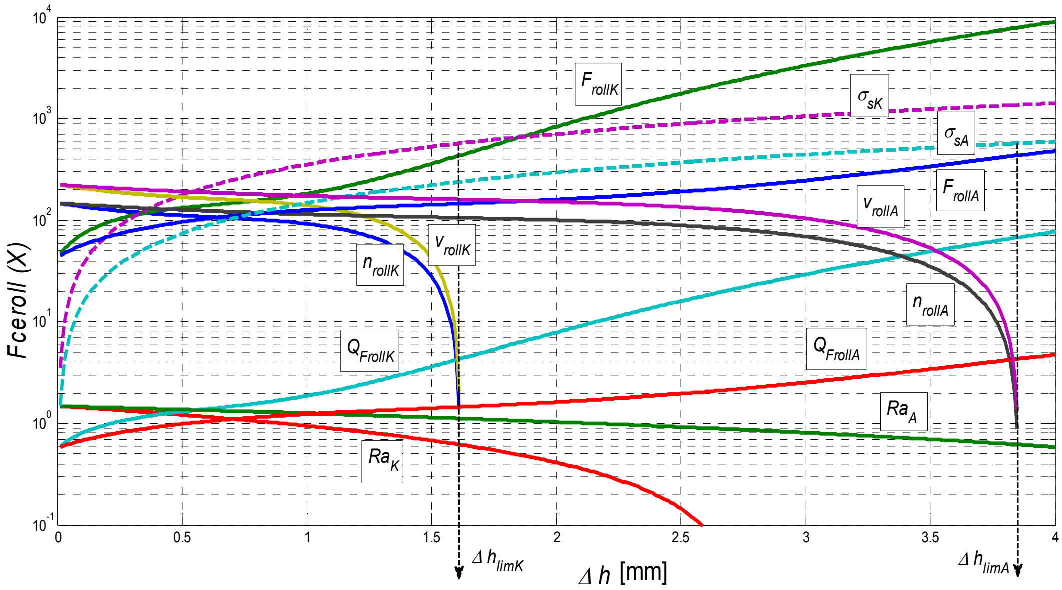

Fig.8. Graphical presentation of prediction of technological parameters in deep-drawing steel KOHAL and aluminium; Y- axis is on a logarithmic scale.

7. VERIFICATION

Verification was performed using the rolling stand on which calculated values of main rolling parameters for individual materials were set accurately. This means rolling speed vrol, and rolling force F_{roll} for selected reductions Δh. These values are plotted in Fig.9. According to reductions, changes of final surface roughness profile Ra_{roll} and final strength Rm of rolled sheets of the mentioned materials were measured and compared with the theoretically predicted values. Changes of the predicted final surface roughness profile Ra_{roll} in comparison with the actually measured surface roughness profile of rolled sheet surface Ra_{rollm} in relation to reductions are represented in Fig.10. Changes of predicted final strength Rm in comparison with the actually measured strength of rolled sheets in relation to reductions are shown in Fig.11. As follows from the comparative graphs and from Table 4. and 5., closeness of the results is high and does not exceed the value of 5 %.

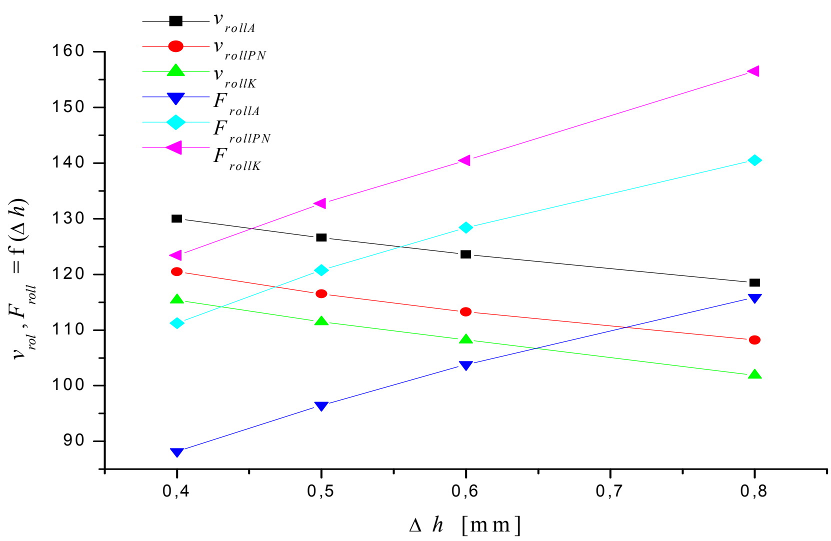

Fig.9. Theoretically determined rolling speed v_{roll}, rolling force F_{roll} for selected reductions Δh in relation to materials.

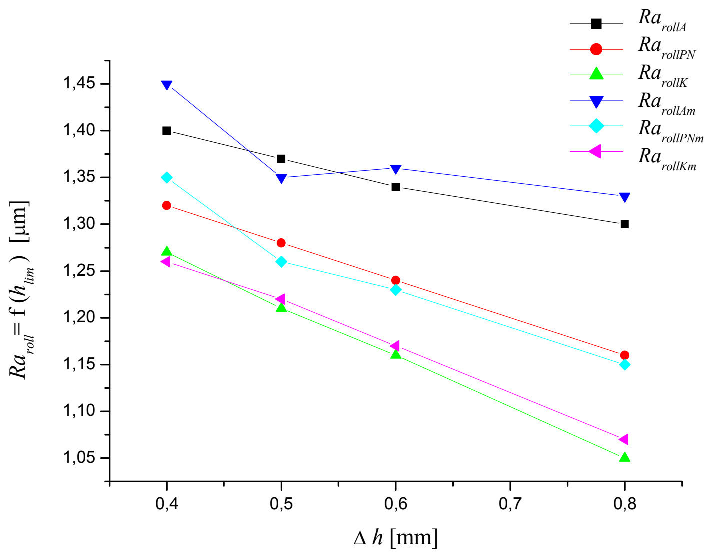

Fig.10. Changes of predicted final surface roughness profile Ra_{roll} in comparison with actually measured surface roughness profile of rolled sheets Ra_{rollm}.

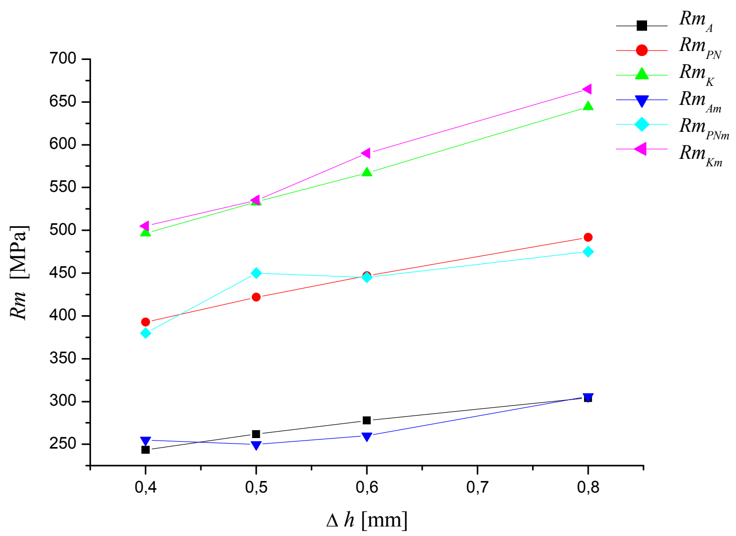

Fig.11. Changes of predicted final strength Rm in comparison with actually measured strength of rolled sheets in relation to reductions.

Table 4. Check of decreasing the surface roughness profile Ra_{roll} [µm] according to Δh [mm]; original sample thickness h =1.6 [mm].

Δh	Ra_{rollA}	Ra_{rollPN}	Ra_{rollK}	Ra_{rollAm}	$Ra_{rollPNm}$	Ra_{rollKm}
0.4	1.4	1.32	1.27	1.45	1.35	1.26
0.5	1.37	1.28	1.21	1.35	1.26	1.22
0.6	1.34	1.24	1.16	1.36	1.23	1.17
0.8	1.3	1.16	1.05	1.33	1.15	1.07
median	1.35	1.25	1.17	1.37	1.25	1.18
$\Delta h = 0$	1.7	1.5	1.45	1.7	1.5	1.45
%	23.53	22.67	27.59	21.76	23.33	26.21

Table 5. Check of increasing the tensile strength Rm [MPa] according to Δh *[mm]*; original sample thickness h =1.6 [mm].

Δh	Rm_{rollA}	Rm_{rollPN}	Rm_{rollK}	Rm_{rollAm}	$Rm_{rollPNm}$	Rm_{rollKm}
0.4	243	393	497	255	380	505
0.5	262	422	533	250	450	535
0.6	278	447	567	260	445	590
0.8	304	492	644	306	475	665
median	272	438	560	268	438	574
$\Delta h = 0$	195	355	470	195	355	470
%	56.03	38.47	37.07	56.92	33.80	41.49

8. CONCLUSION

The authors made the effort to cope with existing disadvantages of the analytical way of proposing rolling parameters for the rolling stand DUO 210 SVa, of course with effect on the optimization of industrial continuous rolling using rolling stands of the type 3,5 KVARTO (results demonstrate close collaboration of the authors with the companies Siemens AG Österreich and ArcelorMittal Ostrava a.s). Especially in industrial rolling, it is a case of large losses in output, quality of rolled material and sheet surface, and as a result, the overall economics of the operation of industrial rolling mills. The reason is still prevailing subjectivity in the selection of main technological parameters of rolling. On the basis of analysis of the data from experimental samples it was possible to propose an algorithm. The proposed mathematical model (algorithm) proved to be suitable in practice, when after entering the input material data it creates a comprehensive mathematical model of the processing numerical and graphical form. An example of graphical representation of the calculation of main functions of the process according to equations in Table 3. is presented in Fig.8. Verification and comparative graphs of theoretically predicted and measured final values of rolled sheets in relation to individual materials and reductions are shown in Fig.10. and Fig.11. The set technological parameters in relation to reductions and materials based on equations in Table 3. are given in Fig.9. The prediction model proves here the significant difference in behaviour of the main functions in the rolling process of materials, namely deep-drawing steel of type KOHAL and aluminium.

It is then possible to determine from the diagram the calculated values of the searched parameter for the chosen absolute reduction Δh and for the chosen (final) surface quality Ra. The optimal technological parameters of the process of rolling for any material can be read from the graph (on vertical lines) for desired surface finish Ra and the given reduction in thickness Δh. According to the prediction graph, constraints in limit values of the size of reductions Δh_{lim} for any material can also be specified. This principle can be analogically expanded as needed also to a number of other required parameters, which can again be expressed both analytically and graphically.

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